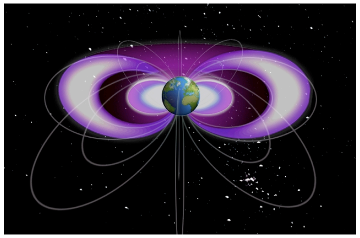

The Radiation Belt Environment Model: Application to Space Weather Now-casting

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Space Plasma Physics Seminar

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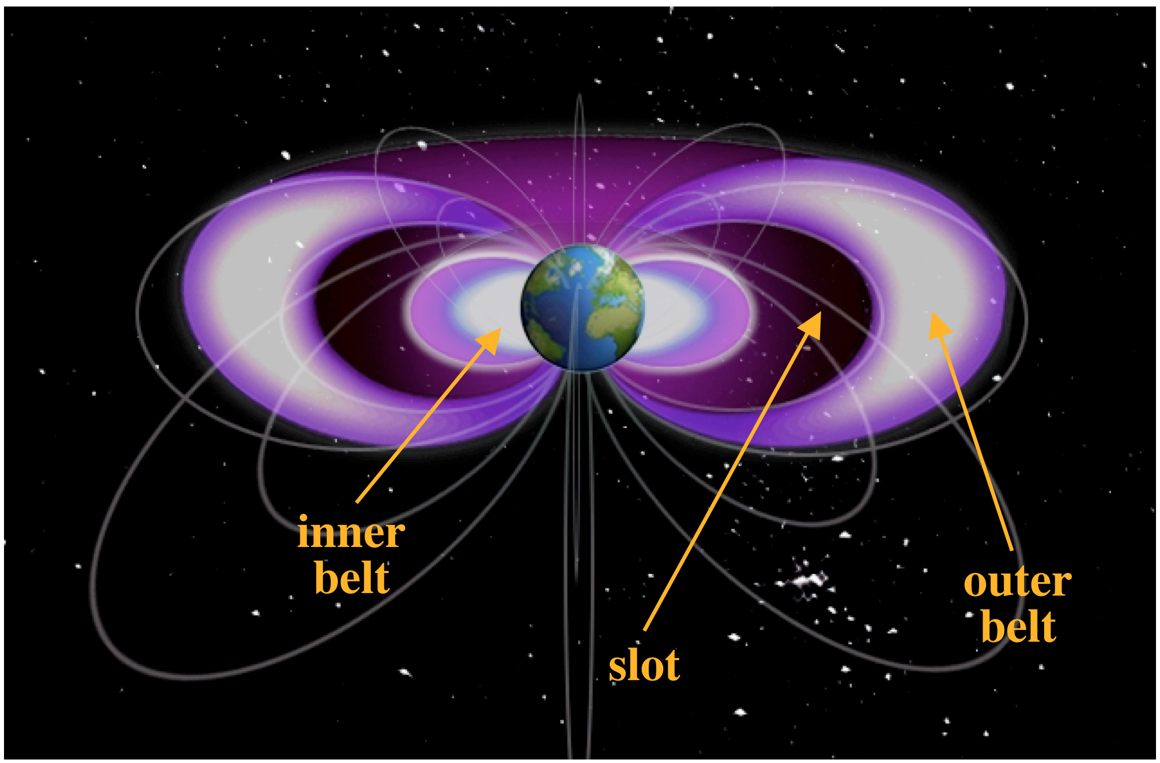
University of Maryland

Outline

- Radiation Belts and their impacts on society
- The **R**adiation **B**elt **E**nvironment (RBE) model
  - Model logic
  - Model formulation
  - Numerical schemes
  - Code architecture
  - Model input/output
- Model the radiation belt enhancements during the storm on 23-27 October 2002
- RBE model and space weather application
- Future works and challenges

The Terrestrial Radiation Belts

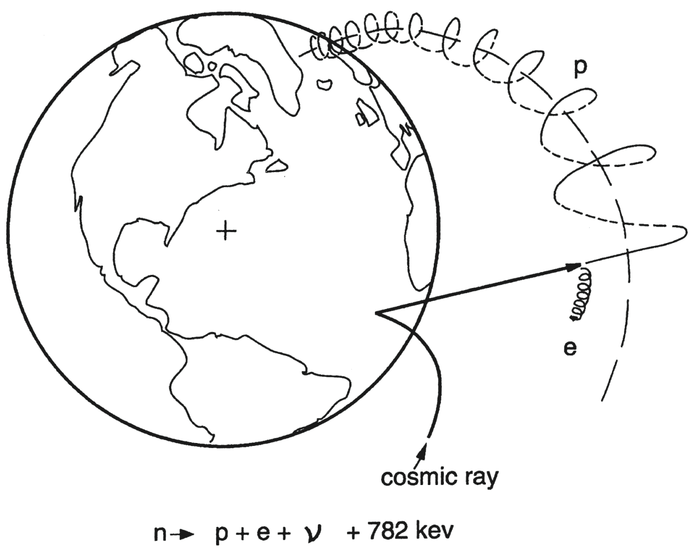
The Earth's radiation belts are energetic (100's keV to 10's of MeV) electrons and ions flowing in the geospace from ~ 0.3 - 8 earth radii altitudes.

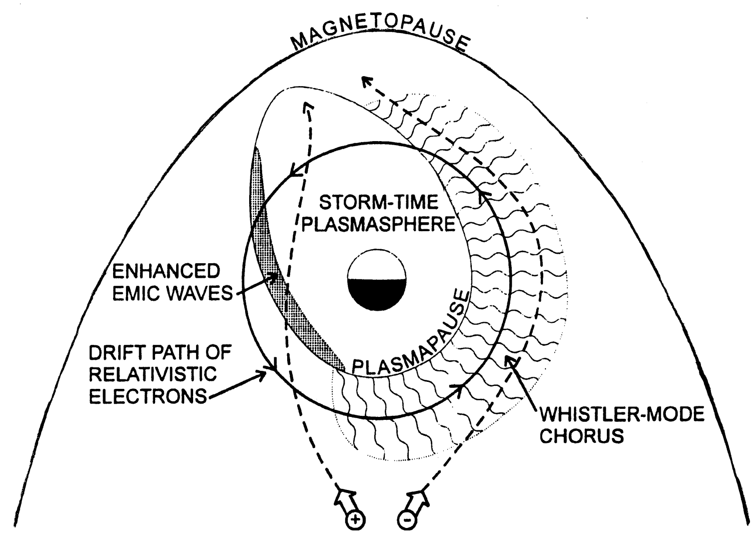


Source and Loss Processes for Radiation Belt Particles

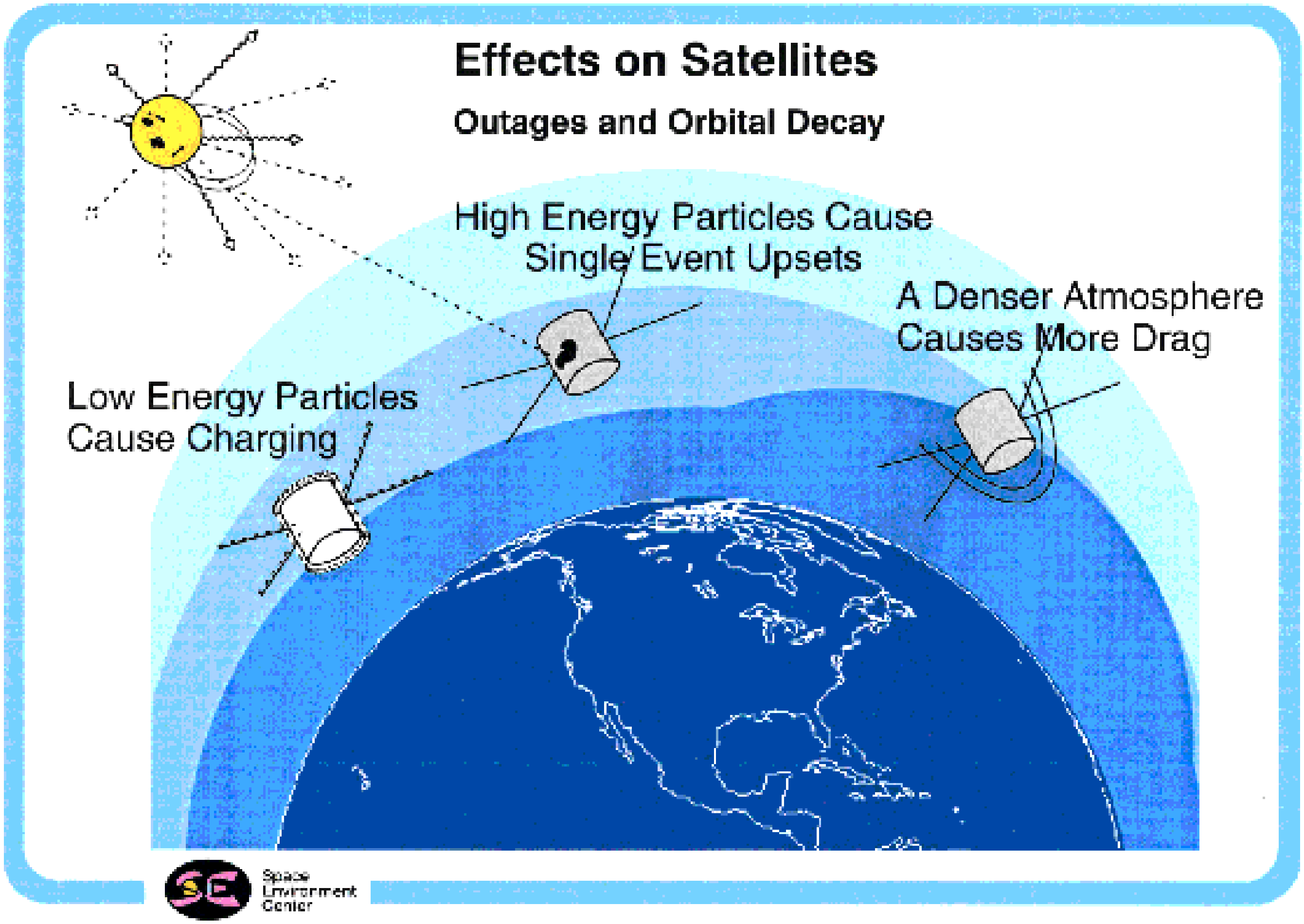
Source: cosmic ray albedo
storm, substorm injections

Losses: wave-particle interactions
dayside drift-out loss



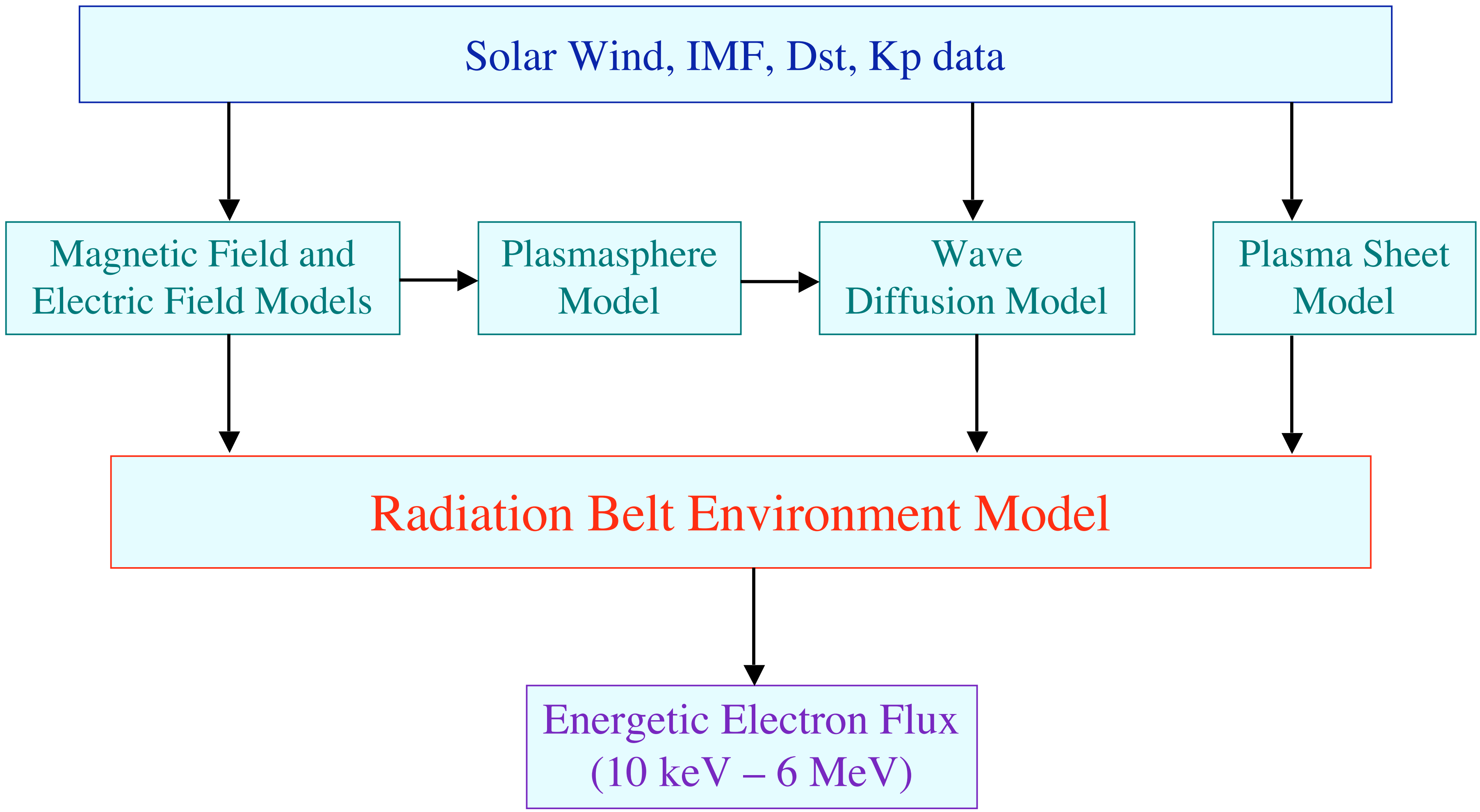


Impacts of the Radiation Belts on Satellites



Space Weather Hazards to Humans

The Radiation Belt Environment (RBE) Model



Radiation Belt Environment Model: The Equation

$$\frac{\partial f_s}{\partial t} + \left\langle \dot{\lambda}_i \right\rangle \frac{\partial f_s}{\partial \lambda_i} + \left\langle \dot{\phi}_i \right\rangle \frac{\partial f_s}{\partial \phi_i} = \frac{1}{\sqrt{M}} \frac{\partial}{\partial M}\left(\sqrt{M} D_{MM} \frac{\partial f_s}{\partial M} \right) + \frac{1}{T(y)\sin 2\alpha_o} \frac{\partial}{\partial \alpha_o}\left(T(y)\sin 2\alpha_o D_{\alpha_o \alpha_o} \frac{\partial f_s}{\partial \alpha_o} \right) - \left(\frac{f_s}{0.5\tau_b} \right)_{\substack{\text{loss}\\ \text{cone}}}$$

$f_s = f_s(t, \lambda_i, \phi_i, M, K)$: phase space density of electrons

λ_i : magnetic latitude at the ionosphere

ϕ_i : magnetic local time at the ionosphere

M : magnetic moment

K : longitudinal invariant

$\left\langle \dot{\lambda}_i \right\rangle, \left\langle \dot{\phi}_i \right\rangle$: drift velocities (convection + magnetic drift + corotation)

D_{MM} : diffusion in magnetic moment due to diffusion in energy, $D_{MM} = D_{EE}\left(\frac{E_o + E}{E_o B_m} \right)^2$

$D_{\alpha_o \alpha_o}$: $f_s^t(M,K) \xrightarrow{\text{mapping}} g_s^t(E,\alpha_o) \xrightarrow{D_{\alpha_o\alpha_o}} g_s^{t+\Delta t}(E,\alpha_o) \xrightarrow{\text{mapping}} f_s^{t+\Delta t}(M,K)$

τ_b: bounce period

Radial diffusion is included implicitly in the time-varying magnetic and electric fields.

Radiation Belt - Ring Current Model: Numerical Schemes

$$\frac{\partial f_s}{\partial t} + \left\langle \dot{\lambda}_i \right\rangle \frac{\partial f_s}{\partial \lambda_i} + \left\langle \dot{\phi}_i \right\rangle \frac{\partial f_s}{\partial \phi_i} = \frac{1}{\sqrt{M}} \frac{\partial}{\partial M}\left(\sqrt{M} D_{MM} \frac{\partial f_s}{\partial M} \right) + \frac{1}{T(y)\sin 2\alpha_o} \frac{\partial}{\partial \alpha_o}\left(T(y)\sin 2\alpha_o D_{\alpha_o \alpha_o} \frac{\partial f_s}{\partial \alpha_o} \right) - \left(\frac{f_s}{0.5\tau_b} \right)_{\substack{\text{loss}\\ \text{cone}}}$$

Fractional Step Approach:

$$f_s^n = f_s(t_n) \longrightarrow f_s^{n+1} = f_s(t+\Delta t) = f_s(t_{n+1})$$

$f_s^{n+1/4} = D_1\left[f_s^n \right]$ $\quad \frac{\partial f_s}{\partial t} + \left\langle \dot{\lambda}_i \right\rangle \frac{\partial f_s}{\partial \lambda_i} + \left\langle \dot{\phi}_i \right\rangle \frac{\partial f_s}{\partial \phi_i} = 0$ $\quad$ Conservation Law, Flux Limited Scheme

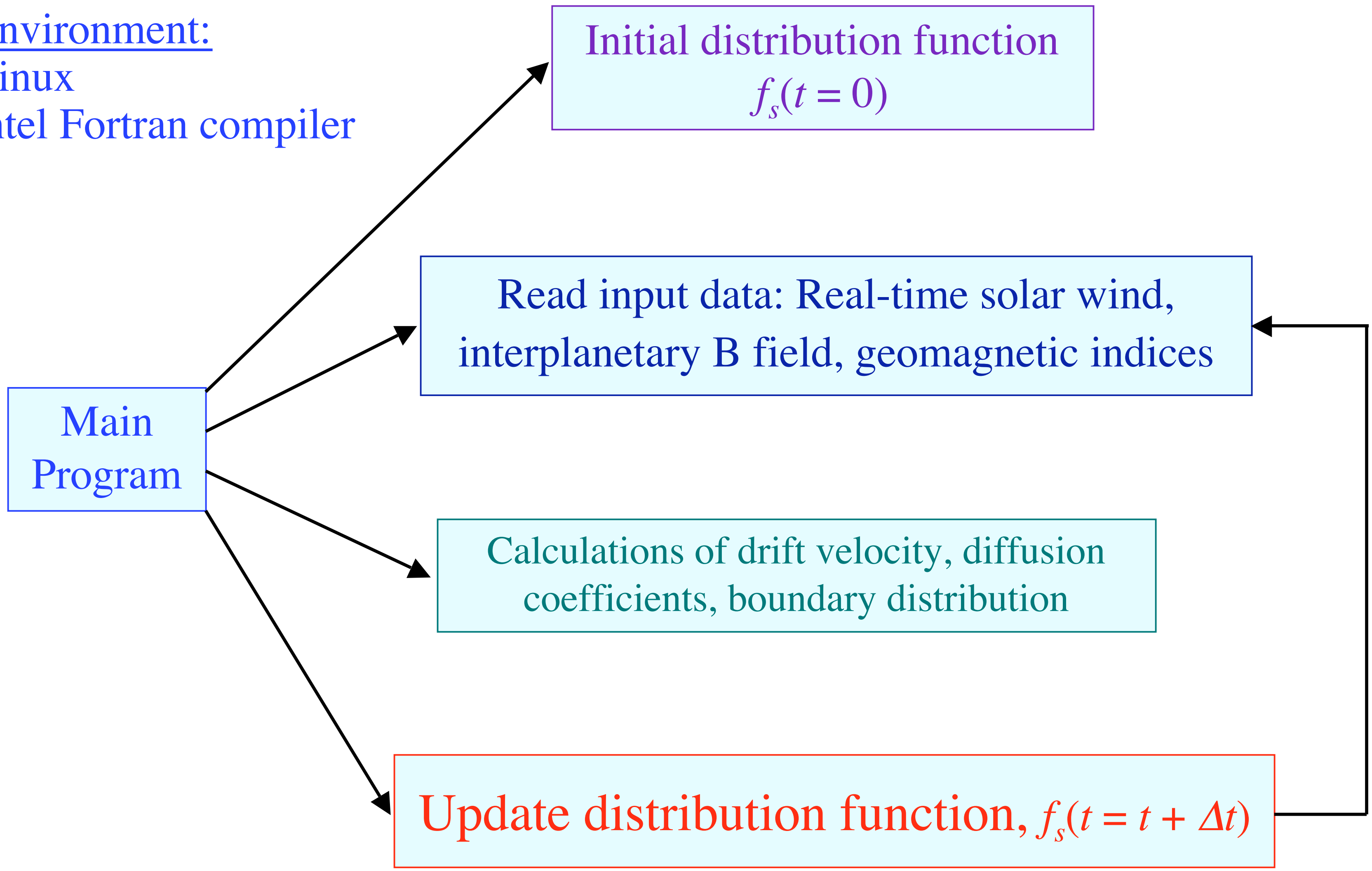
$f_s^{n+2/4} = D_2\left[f_s^{n+1/4} \right]$ $\quad \frac{\partial f_s}{\partial t} = \frac{1}{\sqrt{M}} \frac{\partial}{\partial M}\left(\sqrt{M} D_{MM} \frac{\partial f_s}{\partial M} \right)$ $\quad$ General Crank - Nicolson Scheme

$f_s^{n+3/4} = D_3\left[f_s^{n+2/4} \right]$ $\quad \frac{\partial f_s}{\partial t} = \frac{1}{T(y)\sin 2\alpha_o} \frac{\partial}{\partial \alpha_o}\left(T(y)\sin 2\alpha_o D_{\alpha_o \alpha_o} \frac{\partial f_s}{\partial \alpha_o} \right)$ $\quad$ General Crank - Nicolson Scheme

$f_s^{n+1} = D_4\left[f_s^{n+3/4} \right]$ $\quad \frac{\partial f_s}{\partial t} = -\left(\frac{f_s}{0.5\tau_b} \right)_{\substack{\text{loss}\\ \text{cone}}}$ $\quad$ Exact solution, $f_s^{n+1} = f_s^{n+3/4} \exp\left(-\frac{\Delta t}{0.5\tau_b} \right)$

Radiation Belt - Ring Current Model: Code Architecture

<u>Environment:</u>
Linux
intel Fortran compiler

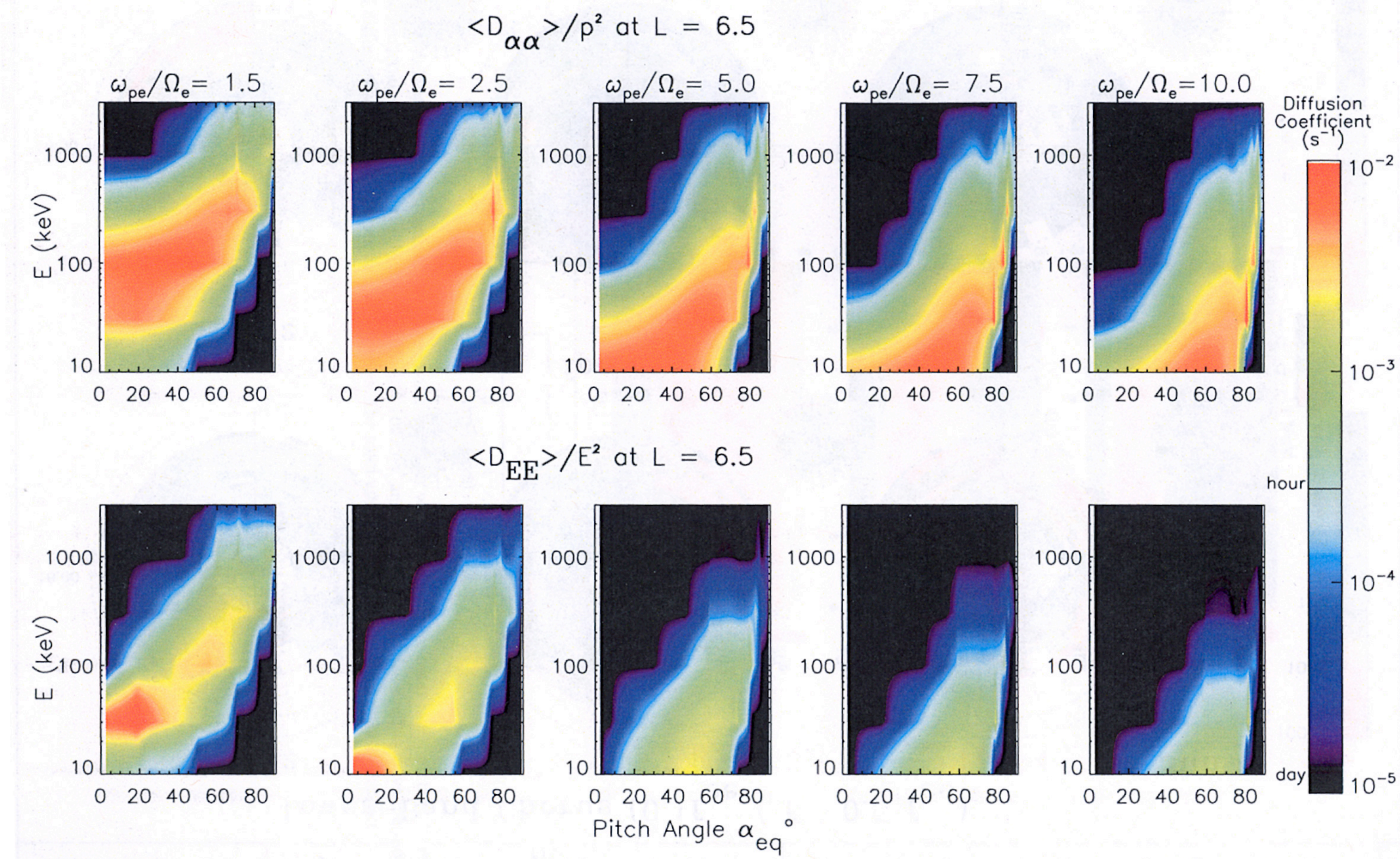


Radiation Belt Environment Model: The Input

- Dst, Kp: Kyoto University Geomagnetic Data Service
- Shifted solar wind, IMF data: ACE or WIND satellite
- Magnetic field model: T96 or T04 model
- Electric field model: Weimer model
- Plasmasphere model: Ober and Gallagher model
- Diffusion coefficients: Horne's PADIE code and CRRES chorus wave data
- Distribution at the nightside boundary (10 RE): kappa distribution
  Nps(t) = [(0.02 Nsw(t-2hr) + 0.316)] sqrt(amu)   cm^-3
  Eo(t) = 0.016 Vsw(t-2hr) - 2.4   keV

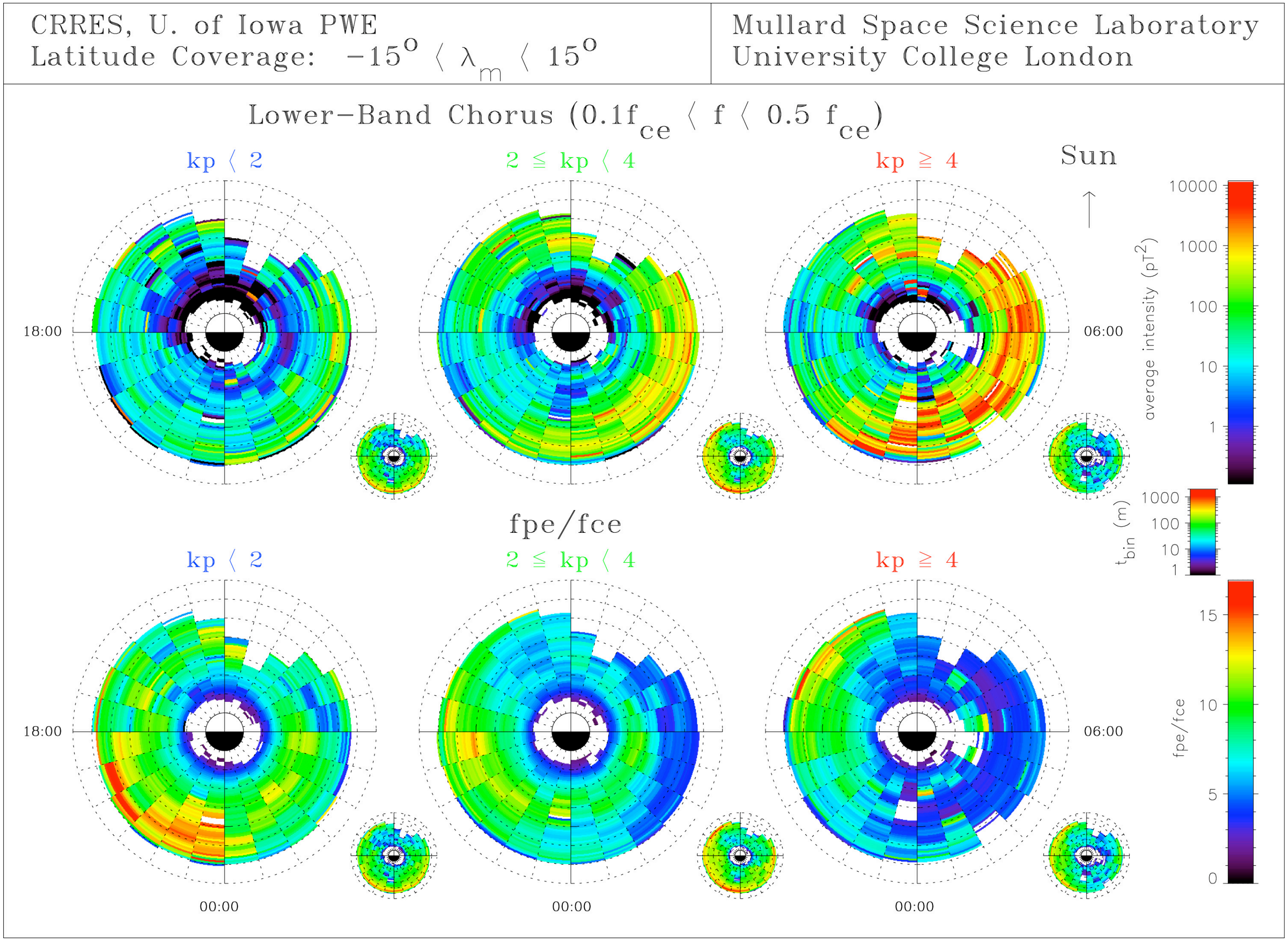
The PADIE Code: Pitch Angle and Energy Diffusion of Ions and Electrons

Electron diffusion rates for whistler mode chorus waves (wave amplitude = 100 pT)



Taken from Horne et al., 2006

CRRES Lower-band Chorus Wave Data

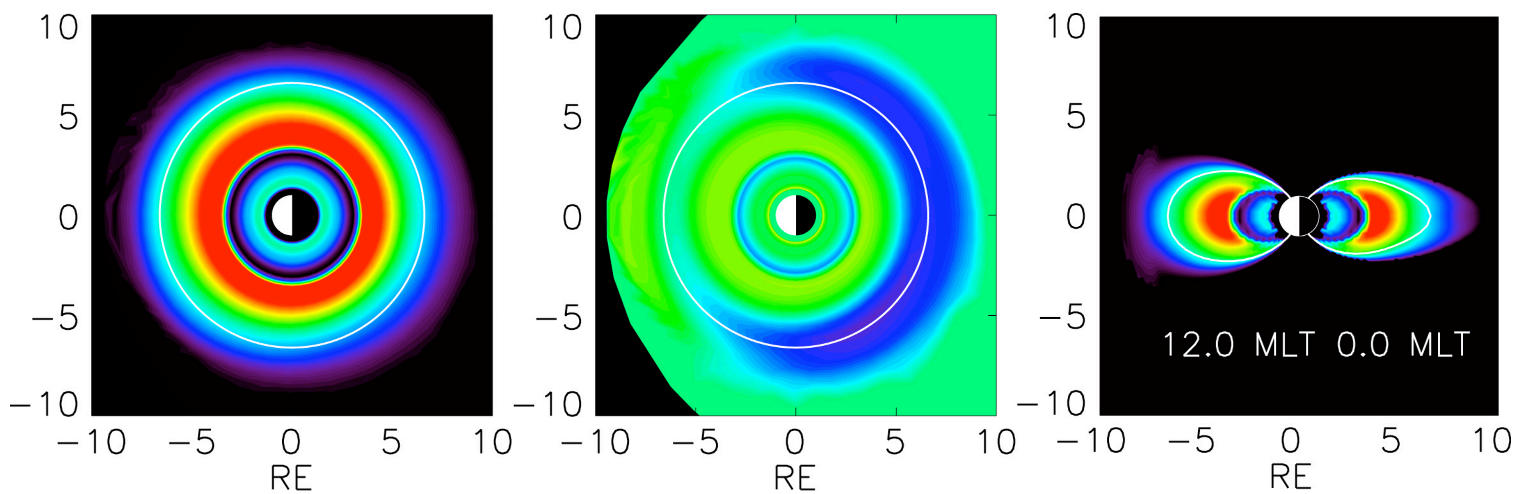


Provided by N. Meredith

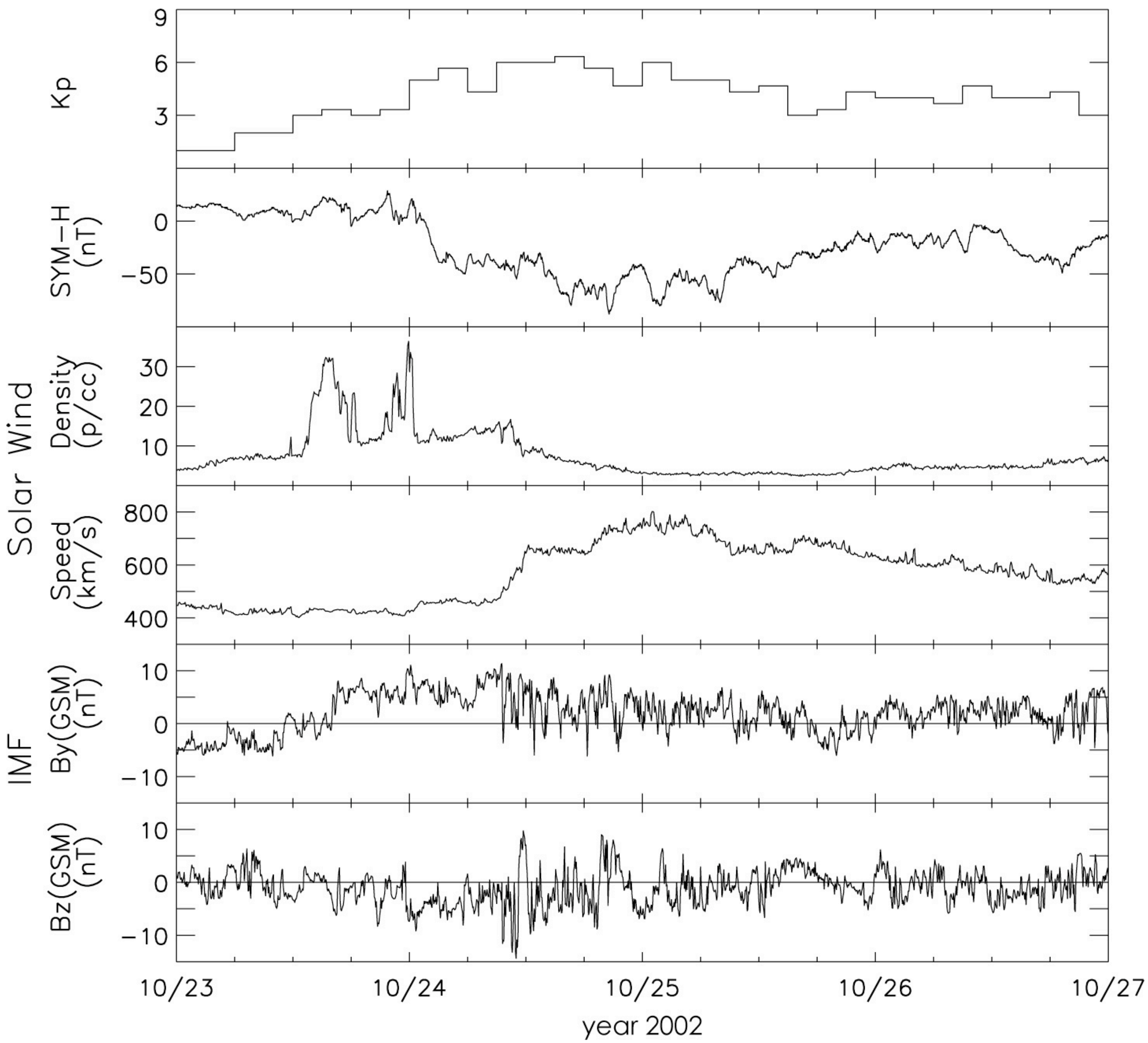
Radiation Belt Environment Model: The Output

RBE Output: 3-dimensional Electron Flux
from 10 keV to 6 MeV at all pitch angles

800 keV electrons

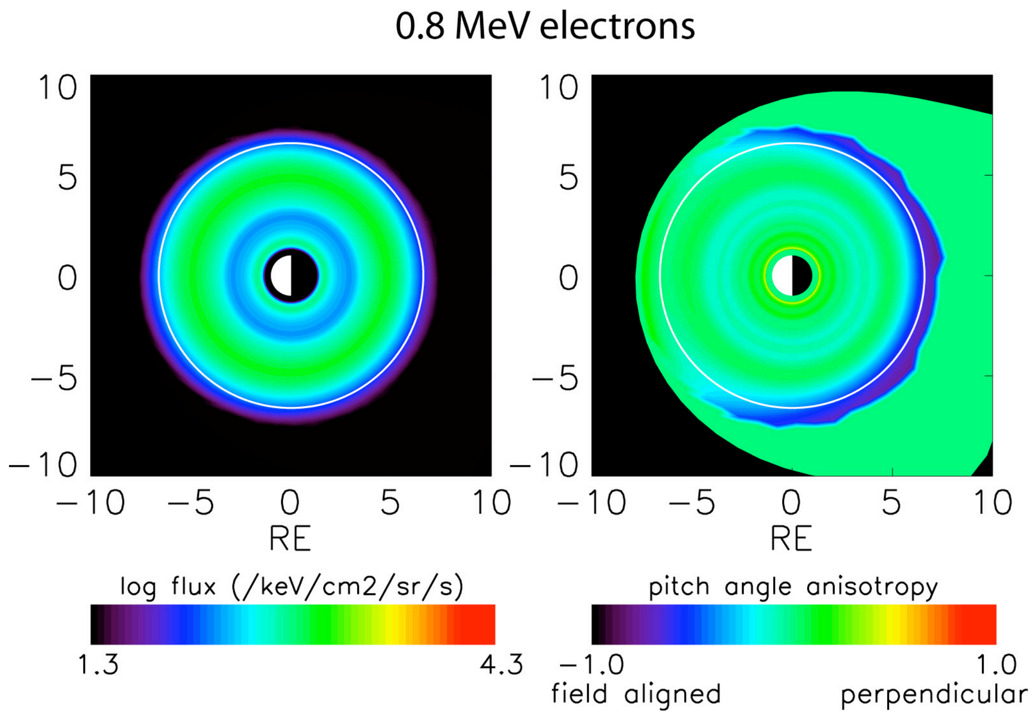


Magnetic Storm on 23 - 27 October 2002



RBE Simulation of the Storm on 23 - 27 October 2002

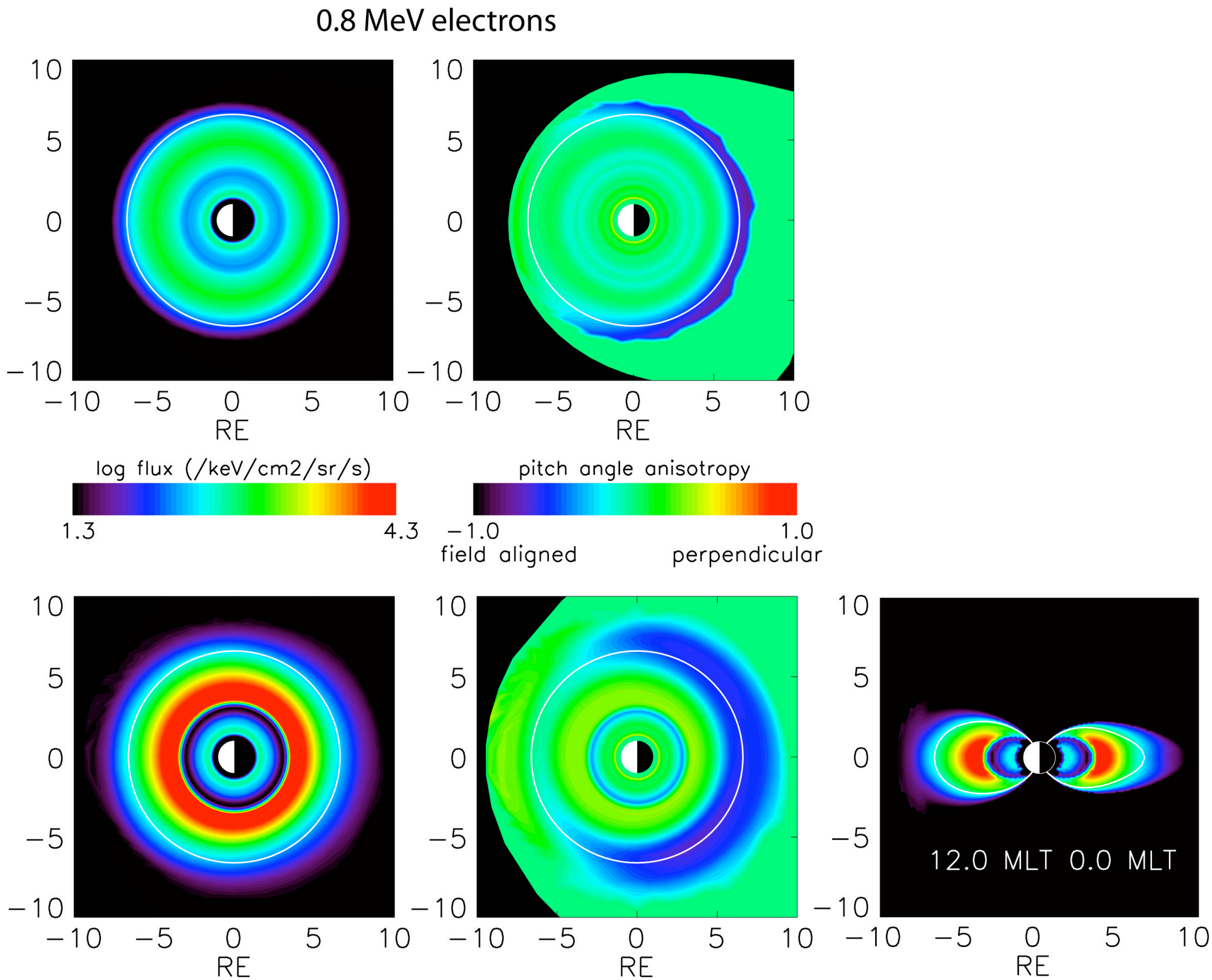
Pre-storm



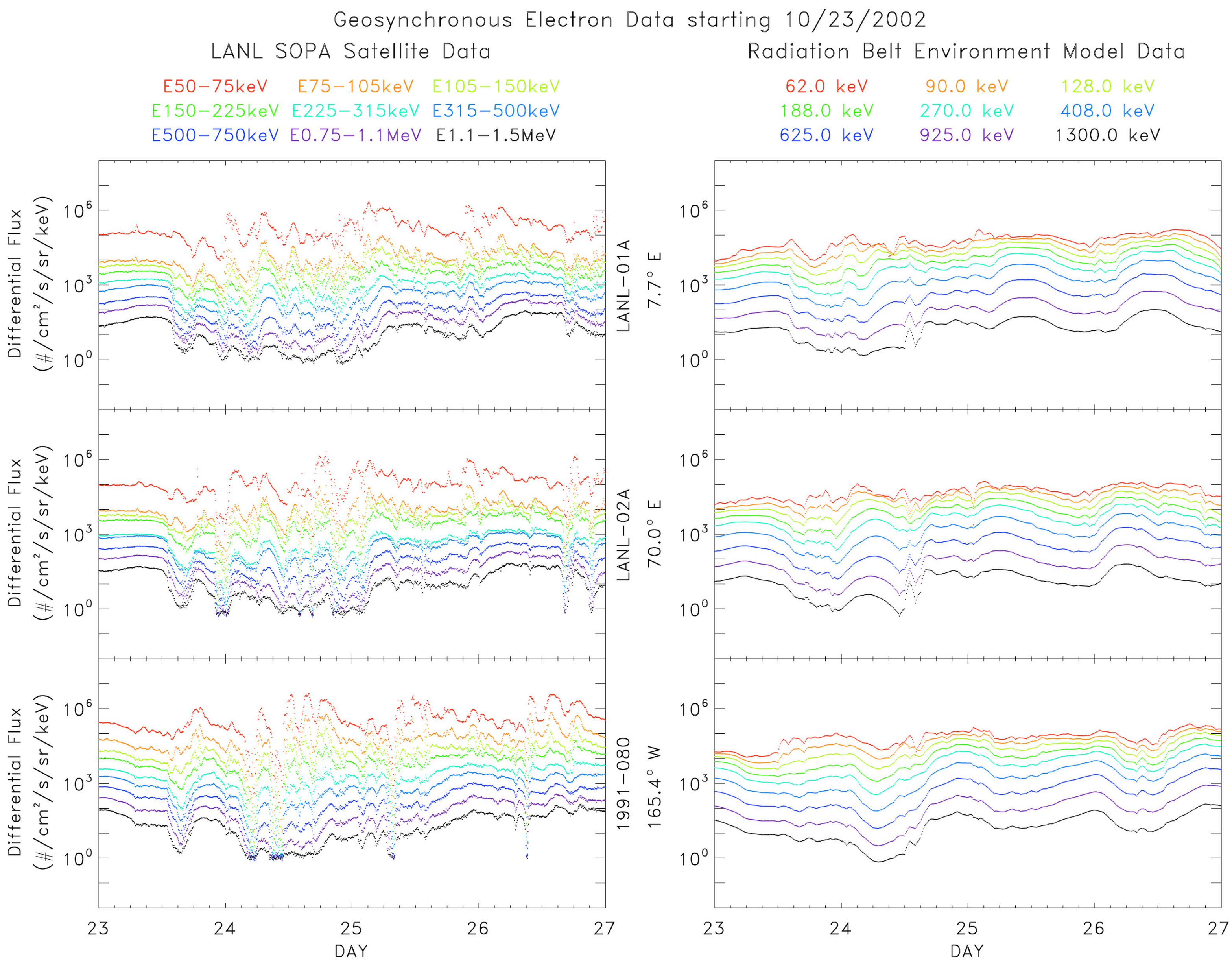
RBE Simulation of the Storm on 23 - 27 October 2002

Pre-storm

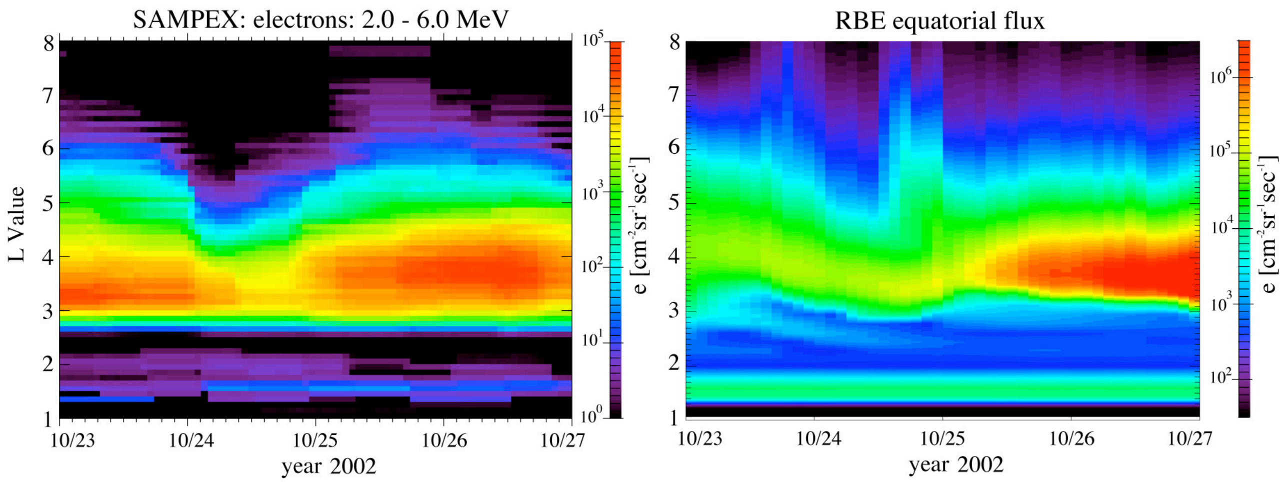
Early recovery



Storm on Oct 23-27, 2002: RBE Simulations versus LANL-SOPA Data



Storm on Oct 23-27, 2002: RBE Simulations versus SAMPEX Data



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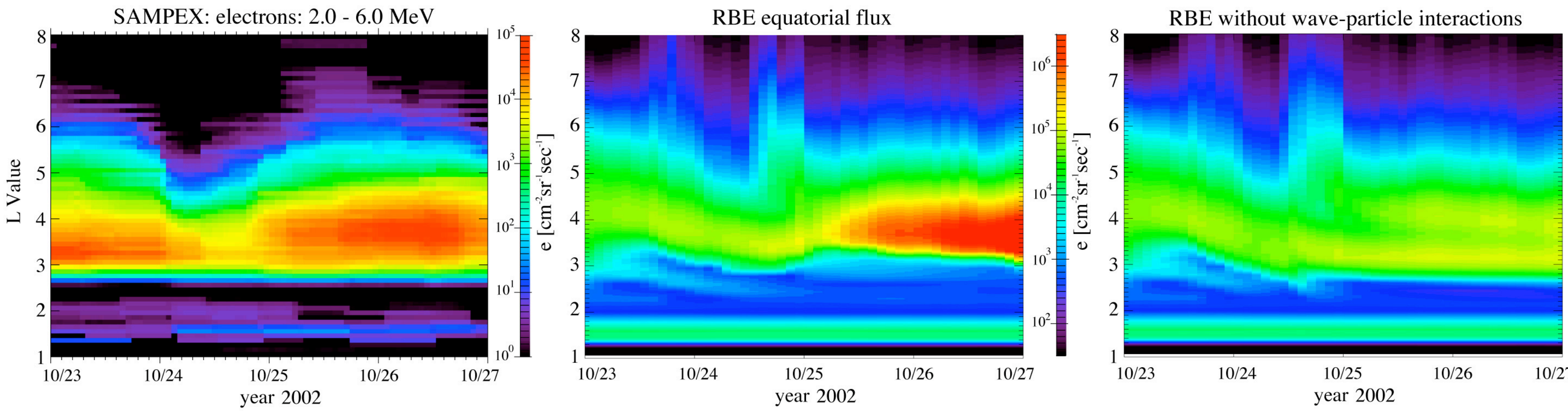
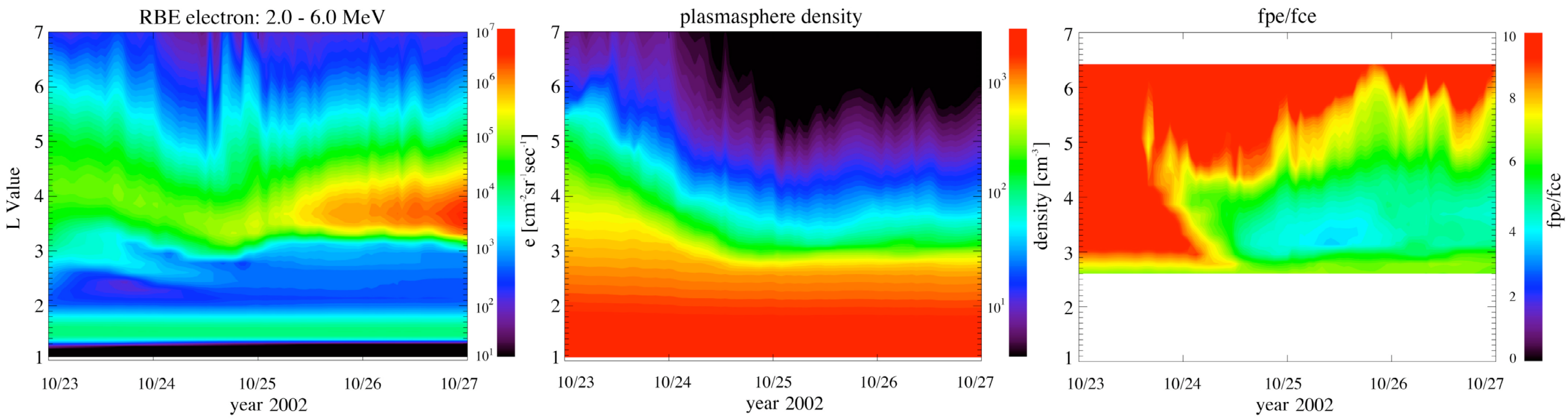
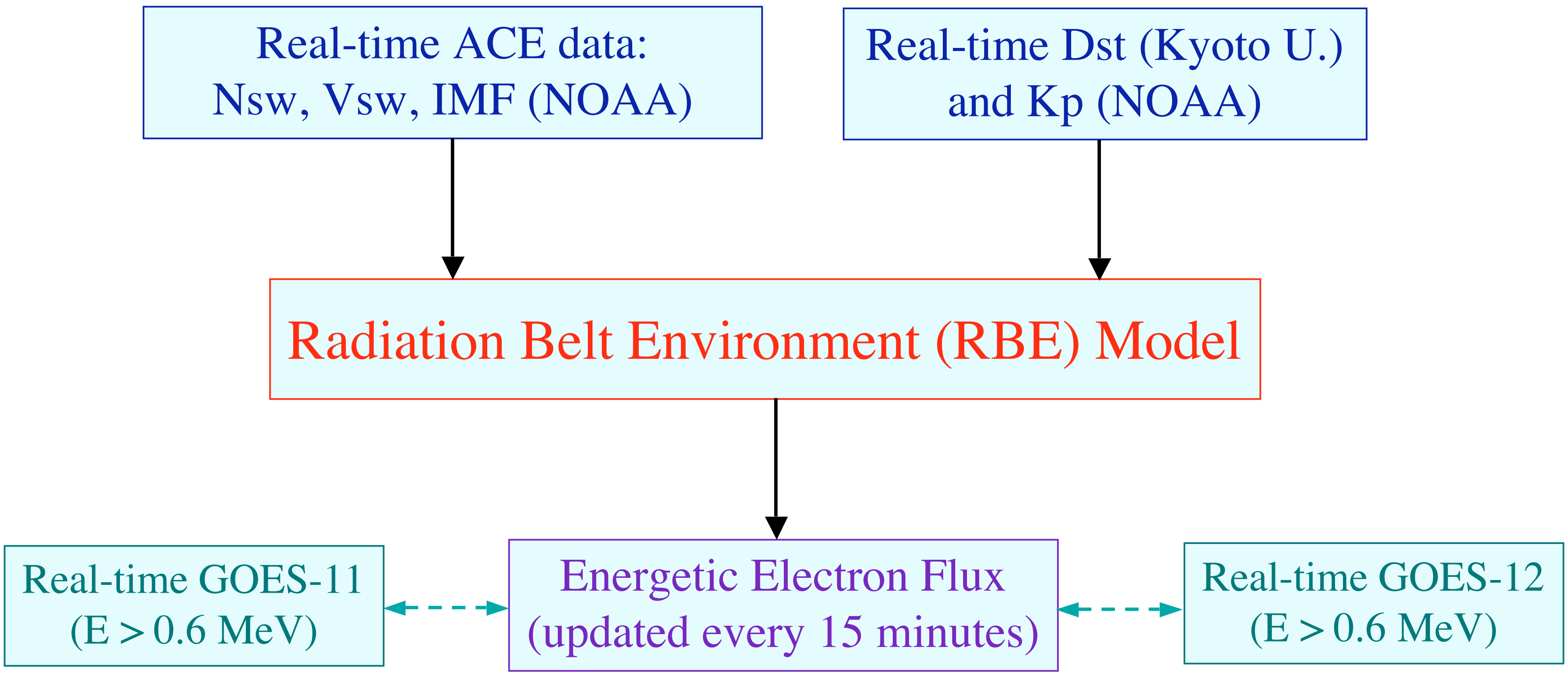


Radiation Belt Electron Acceleration by Whistler Mode Chorus Waves

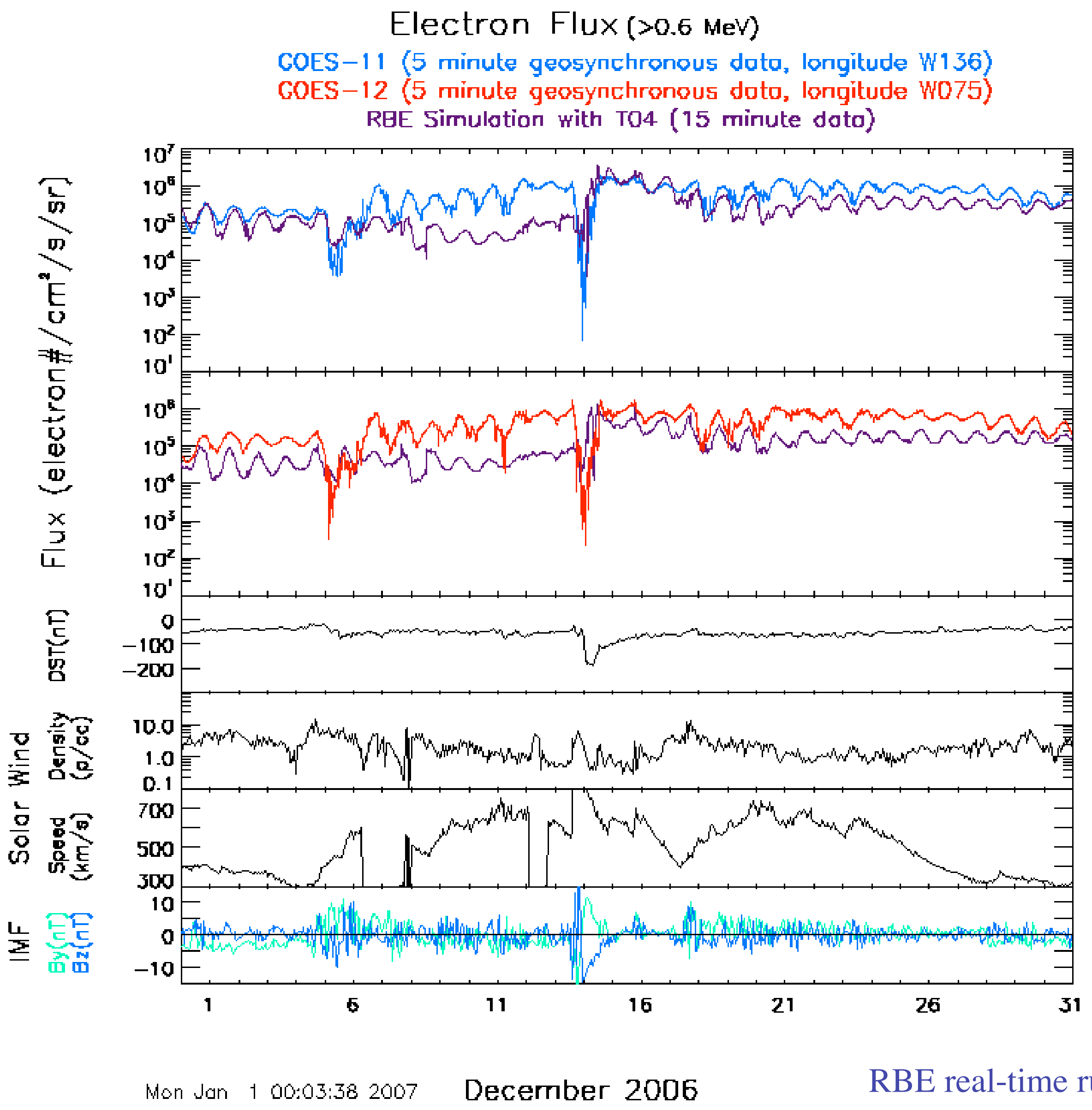


$$\frac{f_{pe}}{f_{ce}} = \frac{1}{B}\sqrt{\frac{n_e m_e}{\varepsilon_o}}$$

The RBE Model Running in Real Time



http://mcf.gsfc.nasa.gov/RB_nowcast/



RBE real-time run by Henry Lo

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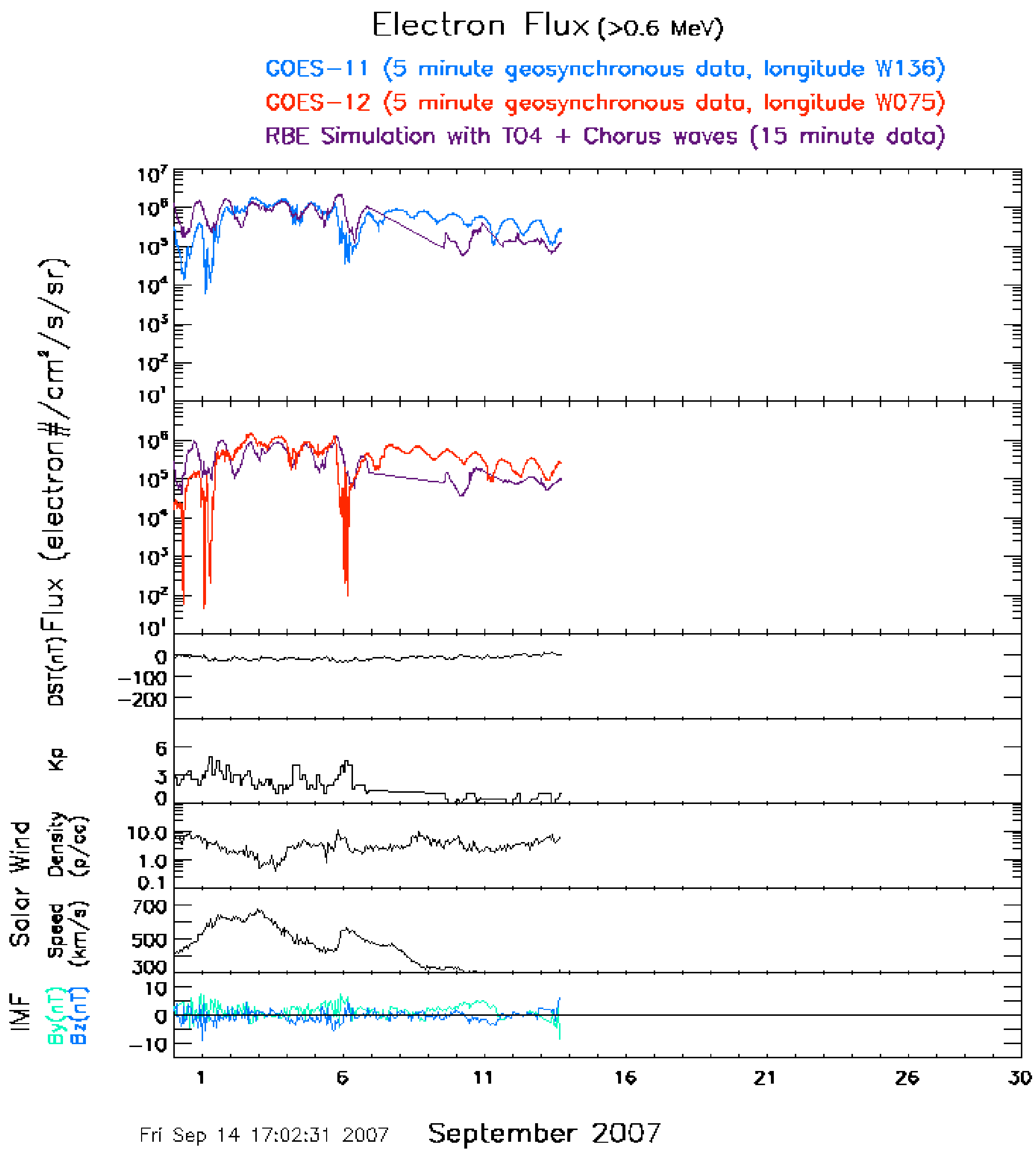
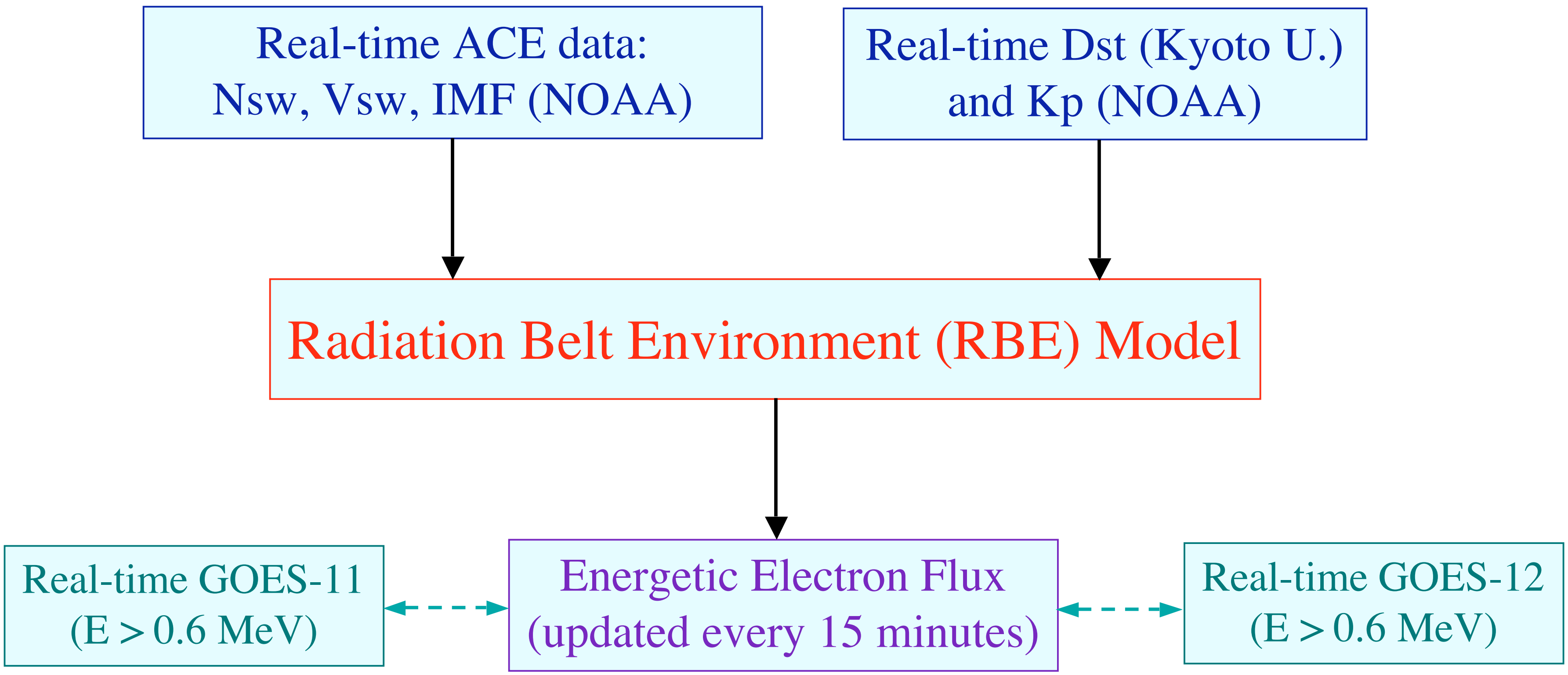
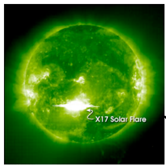


From Now-casting to Forecasting:



From Now-casting to Forecasting: Connecting RBE with a Solar Wind Model



Solar Wind Forecast Model
(i.e., HAF model)

Real-time Dst (Kyoto U.)
and Kp (NOAA)

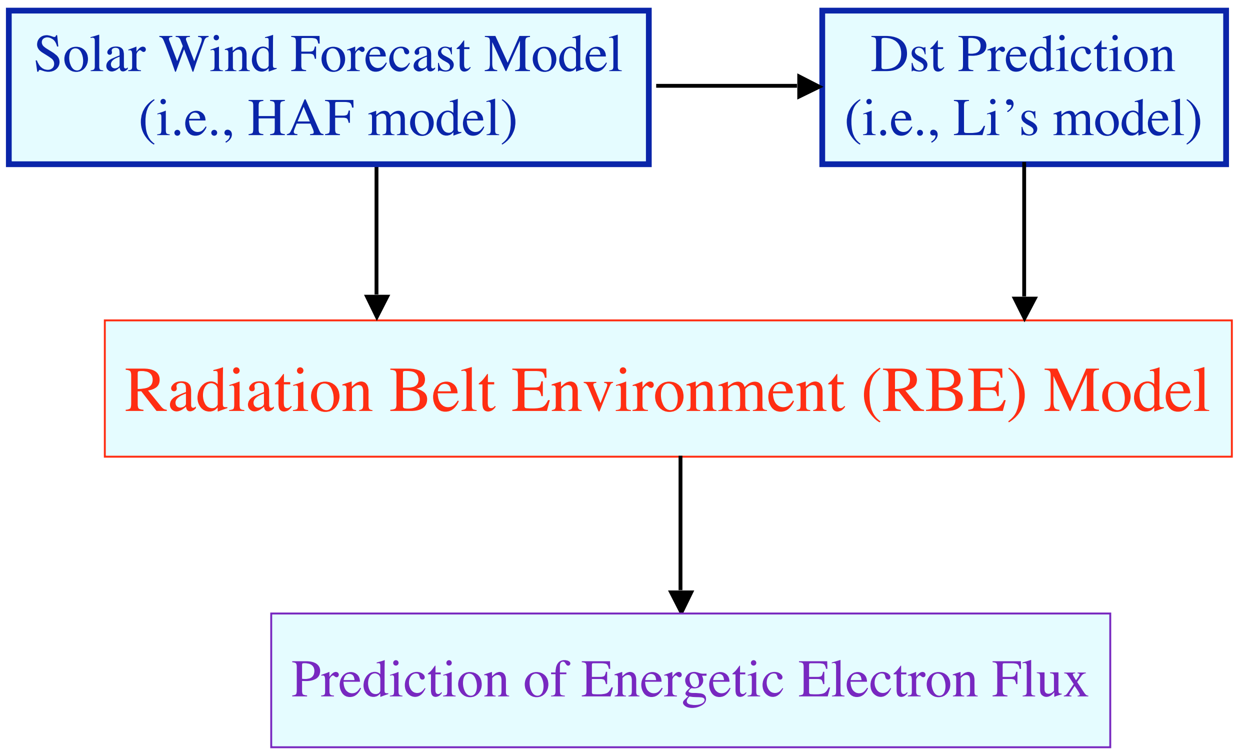
↓

Radiation Belt Environment (RBE) Model

↓

Prediction of Energetic Electron Flux

From Now-casting to Forecasting: Connecting RBE with a Solar Wind Model



Future Works

- Include substorm effects in the radiation belt model
- Include cross-diffusion ($D_{\alpha E}$)

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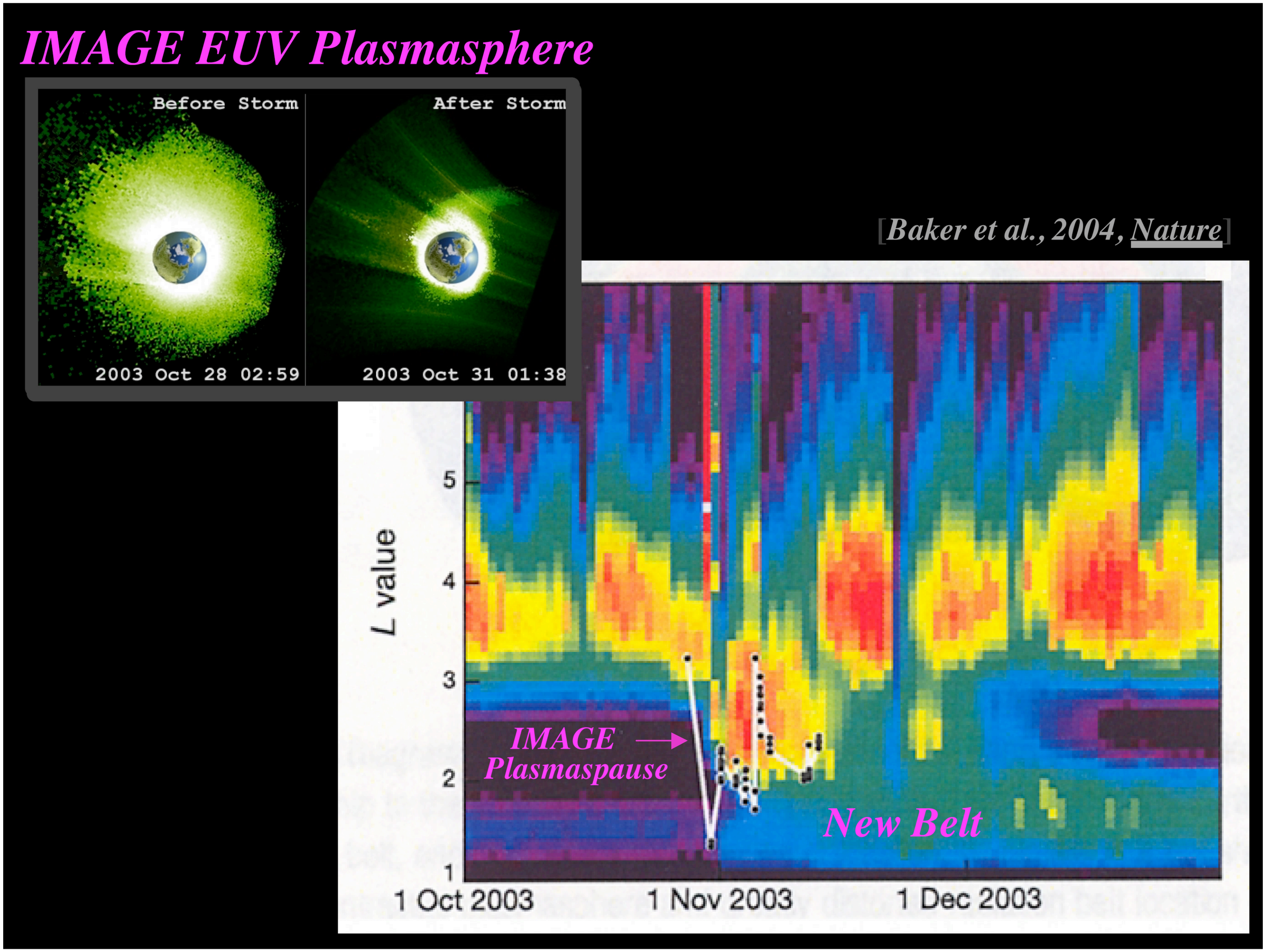
Plasmaspheric Erosion and Formation of New Belt



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- Improve RBE to better model the slot region and the inner belt.

  - self-consistent calculation of wave generation

  - self-consistent B (i.e., force-balance approach)
- Connect the radiation belt model with a solar wind forecast model
- Model validation through extensive data-model comparison with measurements from past missions and future missions (i.e., RBSP)

Summary

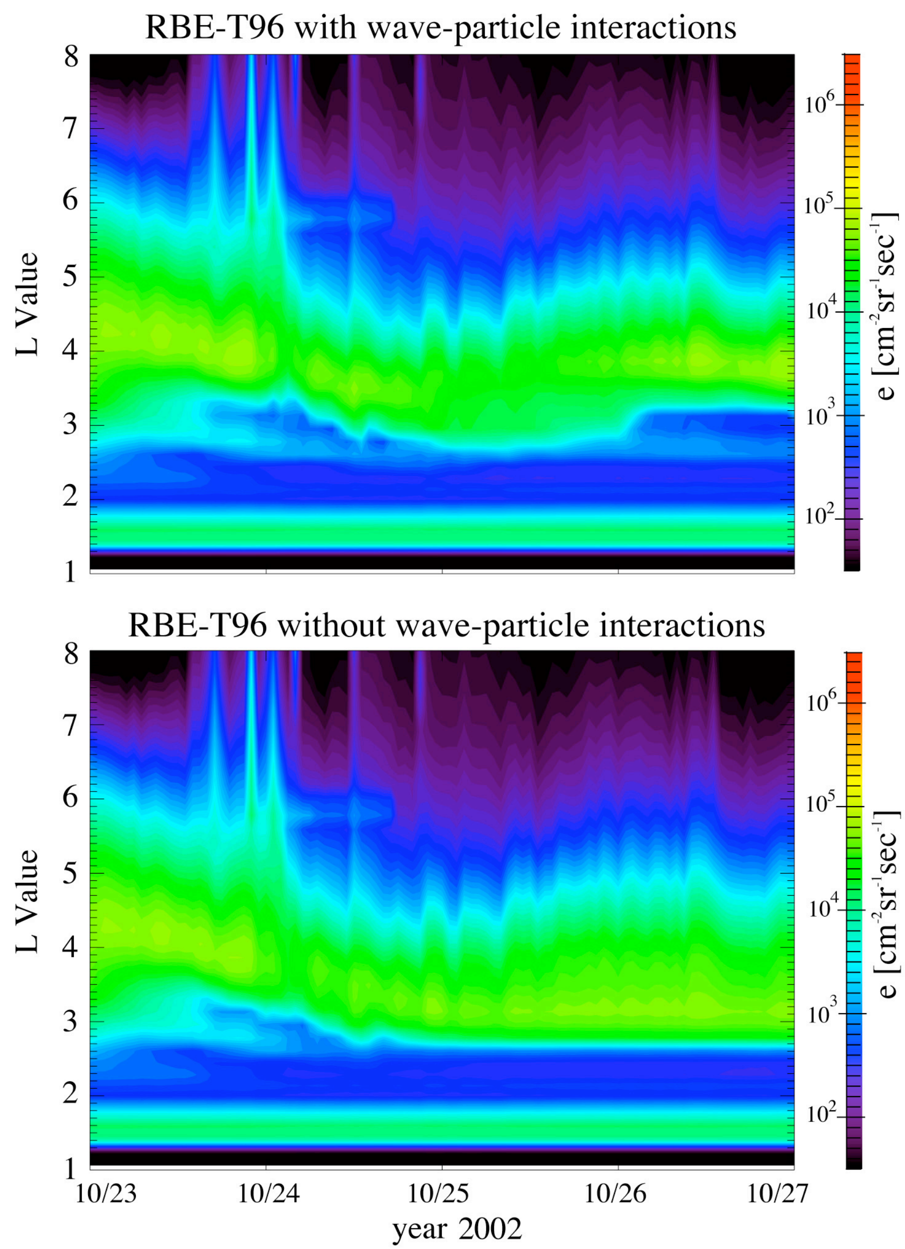
- A data-driven physical model of the radiation belt (RBE model) has been developed to understand the radiation belt dynamics and provide prediction of the radiation belt environment.
- Storm on 23-27 October 2002 was simulated. We found acceleration by chorus waves is responsible for the electron enhancement in the outer belt.
- The RBE model is running in real-time at Goddard and compared with GOES data.
- Future plans:

  - include substorm effects and cross-diffusion

  - self-consistent calculations of wave generation and magnetic field

  - connect RBE with a solar wind forecast model

Backup Slides


RBE-T96 with wave-particle interactions
L Value
e [cm^{-2}sr^{-1}sec^{-1}]
RBE-T96 without wave-particle interactions
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10/23
10/24
10/25
10/26
10/27
year 2002